

Monitoring and Discovering X-ray Pulsars in the Small Magellanic Cloud

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Abstract. Regular monitoring of the SMC with RXTE has revealed a huge number of X-ray pulsars. Together with discoveries from other satellites at least 45 SMC pulsars are now known. One of these sources, a pulsar with a period of approximately 7.8 seconds, was first detected in early 2002 and since discovery it has been found to be in outburst nine times. The outburst pattern clearly shows a period of 45.1 ± 0.4 d which is thought to be the orbital period of this system. Candidate outburst periods have also been obtained for nine other pulsars and continued monitoring will enable us to confirm these. This large number of pulsars, all located at approximately the same distance, enables a wealth of comparative studies. In addition, the large number of pulsars found (which vastly exceeds the number expected simply by scaling the relative mass of the SMC and the Galaxy) reveals the recent star formation history of the SMC which has been influenced by encounters with both the LMC and the Galaxy.

THE EARLY HISTORY OF SMC X-RAY PULSARS

The first known X-ray pulsar in the SMC was the persistent supergiant system SMC X-1. Two luminous transients (SMC X-2, SMC X-3) were discovered with SAS-3. [1]. These were thought to be transient Be/neutron star systems although pulsations were not detected due to the low sensitivity of SAS-3. It was hypothesized that SMC pulsars were exceptionally luminous, possibly related to the low metallicity of the SMC. [2] This was later to be disproved and an alternative explanation found for the high luminosity of the first few SMC X-ray pulsars to be discovered. Over the years a few pulsars were also found with satellites such as ROSAT. [3]

SMC X-RAY PULSARS WITH RXTE

Serendipitous RXTE slew observations in 1997 showed a possible outburst from the vicinity of SMC X-3. Follow up target of opportunity pointed RXTE observation showed a complicated power spectrum with several peaks that were not all harmonically related to each other. Imaging ASCA observations were next made which showed two separate pulsars, however neither was

found to be located at the position of SMC X-3. A more detailed look at RXTE power spectrum showed that in fact three pulsars were simultaneously active [4]. These observations were the first sign of the existence of a very large SMC X-ray pulsar population.

THE RXTE MONITORING PROGRAM

RXTE has been regularly monitoring the SMC since 1997. We have discovered very many transient X-ray pulsars. For those sources where optical counterparts have been identified they are all found to be Be stars. We primarily make weekly observations of one particularly active region near SMC X-3. Other SMC regions have been monitored monthly depending on the amount of time awarded in a particular observing cycle. We use power spectrum to extract pulsed flux from any pulsars. In this way, although the PCA is not an imaging instrument, the pulsed flux from multiple sources can be monitored independently. When new sources are identified we use cross scans in Right Ascension and declination to localize the position of the new sources. Initially scans were done as Target of Opportunity observations. However, this was not always successful if the target had faded before the TOO could be performed. Therefore we

TABLE 1. X-ray Pulsars in the SMC

Pulse Period	Orbital Period	Notes
0.716	3.9	SMC X-1
2.165		XTE J0119-731
2.374		SMC X-2
2.7632		RX J0059.2-7138
3.34		AX J0105-722
4.782		XTE J0052-723
6.848		
7.78		XTE J0055-725 = SMC X-3
8.02		
8.88		
9.13		
15.3		RX J0052.1-7319
16.6		
18.36		
22.07		RX J0117.6-7330
31.0		XTE J0111.2-7317
34.08		
46.4	139	Poor position, not same as 46.6s source?
46.6		XTE, 1WGA J0053.8-7226
51		Same as 25.5s
58.97	123	XTE J0055-724
74.7		AX J0049-729
82.4		
89		
91.1	88.25	AX J0051-722
95.2		
101.4		AX J0057.4-7325
138.0	125	Optical period
140.1		XMMU J005605.2-722200
144	61	
152.1		
164.7		
169.3		XTE J0054-720
172.4		
202		XMMU J005920.8-722316
263.6		XMMU J004723.7-731226
280.4		
304.49		
323		RX J0050.8-7316
348/343		rapid spin down
455+-2		RX J0101.3-7211
503.5		
564.83		
701		
755.5	394	RX J0049.7-7323

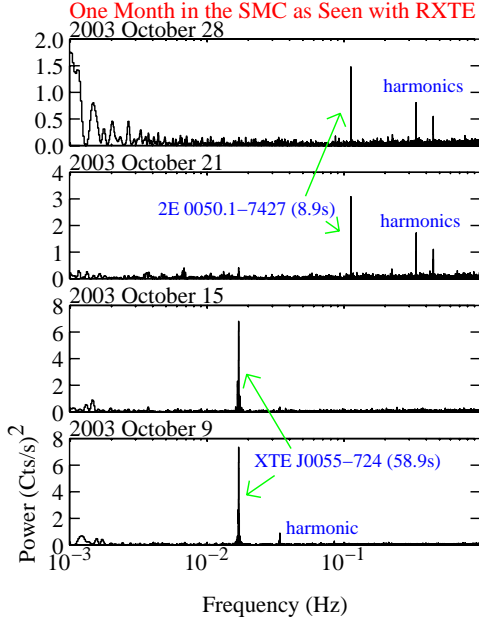


FIGURE 1. Examples of one recent month of RXTE observations of the SMC. A power spectrum is shown for each weekly observation in this month and pulsar detections are marked.

currently include R.A./dec. scans in all our SMC observations. For new sources we thus obtain at least minimal positional information. However, position determination can be problematic if too many pulsars are simultaneously active. A log of known X-ray pulsars in the SMC is currently maintained at <http://heawww.gsfc.nasa.gov/~corbet/pulsars/>.

ORBITAL PERIODS

Ten pulsars have candidate orbital periods determined by us from long term periodicities in their pulsed flux [5]. The statistical significance of the orbital period determinations varies depending on, for example, the number of outbursts detected and whether the outbursts are “type I” or “type II” (i.e. related to periastron passage or not). In addition, optical monitoring of optical counterparts, has also revealed the orbital periods of several systems [6] [7]. For those sources where only a small number of outbursts have been seen so far continued monitoring should conclusively pin down the orbital periods. For two SMC X-ray pulsars we have very solid orbital periods determined from fairly recent observations. For the 7.78s pul-

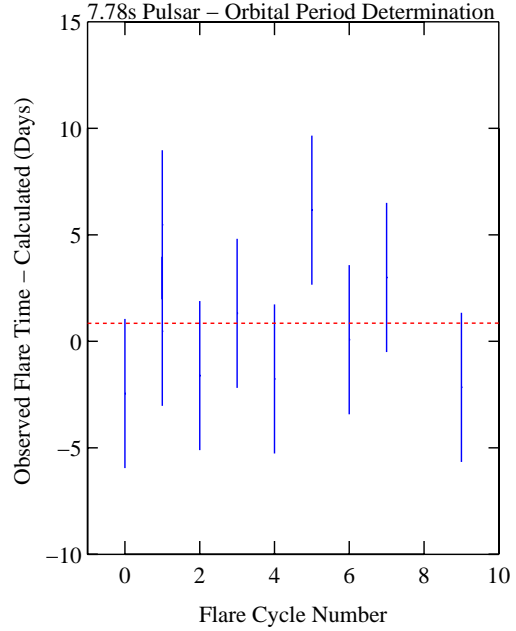


FIGURE 2. Determination of the orbital period of the 7.78s pulsar recently identified as SMC X-3. [8]

sar (recently determined to be SMC X-3 [8]) we observed 9 outbursts in 2002 and early 2003. All of these outbursts are consistent with $P_{orb} = 45.1 \pm 0.4$ days. More recently, a set of five outbursts from the 144s pulsar in 2003 and 2004 have revealed an orbital period of 61.4 ± 1.1 days.

The orbital periods derived so far appear to follow the correlation between orbital period and spin period found for Galactic Be star systems (see e.g. Corbet 1986 [9]).

WHY ARE THERE SO MANY PULSARS IN THE SMC?

A simple scaling based on the relative masses of the SMC and Galaxy predicts only ~ 2 SMC X-ray pulsars. However about 45 are now known and are listed in the table. A more realistic prediction of the expected number of X-ray pulsars in the SMC should come from the star formation rate as high-mass X-ray binaries have rather short lifetimes. However, estimates of the current star formation rate in the SMC do *not* give very large numbers. Estimates of the SMC star formation rate from integrated colors [10] and from H α [11] give 0.064 and 0.046 M_{\odot}/yr respectively compared to the Galactic star formation rate of a few M_{\odot}/yr . However, SMC has ex-

THE POTENTIAL OF THE SMC PULSAR DATABASE

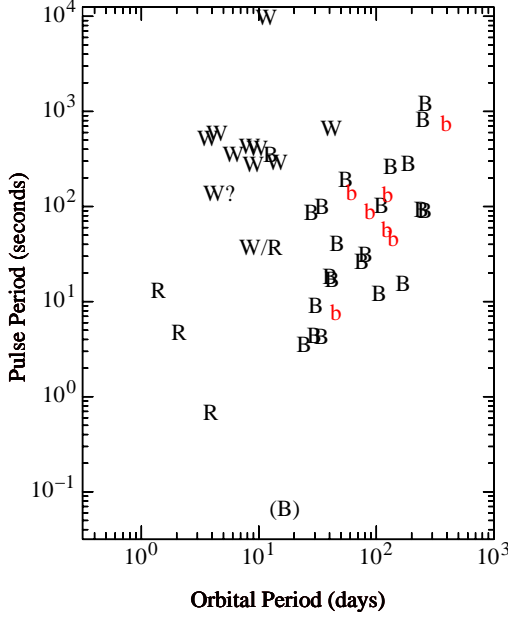


FIGURE 3. Orbital and spin periods of high-mass X-ray binaries. ‘R’= Roche-lobe overflow mass transfer, ‘W’= wind accretion system, ‘B’= Galactic Be star source, ‘b’= SMC Be star source, ‘(B)’= LMC Be star source.

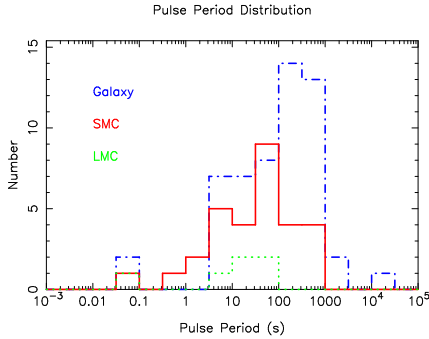


FIGURE 4. A comparison of the pulse period distributions of the SMC, Galaxy, and the LMC [5]. Note that that distributions are *not* normalized but show absolute numbers of pulsars. The SMC distribution does not contain several recently discovered X-ray pulsars.

perienced encounters with LMC and Galaxy in past and these encounters likely triggered bursts of star formation (see e.g. Yoshizawa & Noguchi 2003 [12]). The remnants of this star formation burst may now be seen as high mass Be star X-ray binaries.

All the SMC pulsars lie at approximately the same distance (although the SMC does have a substantial depth). This facilitates comparative studies (e.g. pulse profiles) as function of luminosity. We are continuing to build up a huge X-ray pulsar database with RXTE which can be used to study pulsar parameters in many different ways. For example, we can now start to compare the pulse period distributions and the pulse/orbital diagrams for the SMC and the Galaxy. One notable difference so far between the SMC and the Galaxy is the apparent lack of supergiant wind accretion systems in the SMC. In the Galaxy these sources have luminosities of a few 10^{36} to 10^{37} ergs/s and, unless the SMC’s lower metallicity causes such systems to have very much lower luminosities, should be detectable in our observations which have limiting luminosities of roughly 10^{36} ergs/s. Although our weekly monitoring observations have durations of about 7000s, which makes them somewhat less sensitive to the longer pulse periods exhibited by wind accretion systems, we have had some longer duration observations and long Chandra and XMM observations should also have been sensitive to detection of this type of system. The overall pulsar properties of the SMC can tell us about the relative evolution of a very nearby galaxy and we can compare source count properties with predictions of various models.

SMC PULSAR MONITORING BEYOND RXTE

Although Chandra and XMM are sensitive to source detection, neither is well suited to frequent monitoring to determine orbital periods. The RXTE ASM is just sensitive enough to detect the brightest (10^{38} ergs/s) outbursts from reasonably isolated SMC sources such as SMC X-2 [13]. One more sensitive ASM that may have potential for the long term study of the SMC pulsars is the Lobster All Sky Monitor that will be installed onboard the International Space Station. [14] This instrument should be very sensitive but source count rates will be low. Additionally, lobster-type instruments are not sensitive to harder X-rays. The ideal type of instrument with which to conduct long term SMC X-ray pulsar studies may well be an imaging instrument of several degrees FOV such as on the proposed MIRAX mission [15], continuously staring at SMC.

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